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The design, development and performance evaluation of thermoelectric generator (TEG) integrated forced draft biomass cookstove

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Abstract

The new developments in cookstove design have been made for better usage of sustainable energy and reducing the worse impact of climate change on environment. A cookstove is a combustion device which liberates lot of heat energy during cooking. In the recent developed design of TEG integrated forced draft biomass cookstove, the liberated waste heat energy is utilized for generation of electricity with the help of a thermoelectric generator. A power of 5W is achieved through the thermoelectric generator. The generated electricity is stored in a Li-ion battery and used further for running a 12Vd.c. fan, lighting a LED light, and charging a mobile phone. The novelty in charging a Li-ion battery is to run a fan for domestic biomass cookstove for cleaner combustion. The fan is also used for cooling one side of TEG through heat sink for improving electrical performance of TEG and thus improving the combustion of the cookstove. This cookstove has been deployed in the rural areas to check its usability, viability, electrical and thermal performance under the umbrella of clean combustion.

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Keywords: Thermoelectric generator; cookstove; waste heat; combustion.

1. Introduction

According to the WHO report about 3 billion people cook in open fires by burning biomass like wood, animal dung, crop waste and coal. Over 4 million people die prematurely from illness due to the household air pollution by

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cooking with solid biomass fuels[1]. The incomplete combustion of these solid biomass fuels causes dense soot formation which is highly hazardous to women and small children residing in the cooking area. According to International Energy Agency (IEA), nearly 1.3 billion people did not have access to electricity in 2009. In this scenario it is necessary to provide electricity as well as clean cooking. The clean combustion by solid biomass fuels depends on the air-to-fuel ratio. If sufficient amount of air is supplied during combustion the formation of soot and carbon mono-oxide tends to reduce. This air supply ratio during combustion can be increased by implementing a fan with cookstove.

Nomenclature

TEG	thermoelectric generator	R_L	load resistance (Ω)
A	area of TEG module (m2)	I	current (A)
k	thermal conductivity (Wm-1k-1)	P	power (W)
VL	load voltage (V)	R_{int}	internal resistance (Ω)
V_{oc}	open circuit voltage (V)		
T_c	cold side temperature of TEG (°C)	*Greek symbols*	
TH	hot side temperature of TEG (°C)	α	Seebeck coefficient (V/K)
QH	heat flux of one TE module on hot side (W)	ρ	resistivity (Ω.cm)
Q_c	heat flux of one TE module on cold side (W)	ΔT	temperature difference (°C)
SEPIC	single-ended primary inductance converter.	η	efficiency (%)

In India 66% of the total population rely on the traditional use of biomass for cooking and 25% population do not have the access to electricity[2]. The places where have long power cuts, the thermoelectric generator integrated cookstove play an effective role.

2. Thermoelectric principles

The TEG is a semiconductor device which converts heat energy directly into electrical energy. A TEG consists of number of cubical semiconductor blocks and it appears like a plate. The heat is applied to one face of it and the other face is kept relatively cool. The principle of TEG states that the difference in temperature in two sides of the TEG generates electricity. Hence, according to Thomas J. Seebeck in 1821, a potential difference could be produced by a circuit made from two dissimilar wires when one of the junctions was heated[10]. This is called Seebeck effect. The e.m.f. is proportional to the temperature difference. The potential difference is given as: $V = \alpha\Delta T$. One thermoelectric module comprise of two different semiconductor materials also known as Seebeck cells or thermo elements each of p-type and n-type cells which are connected electrically in series and thermally in parallel.

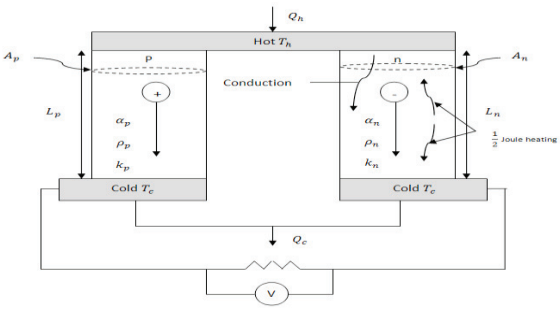


Fig. 1. Single thermocouple[10]

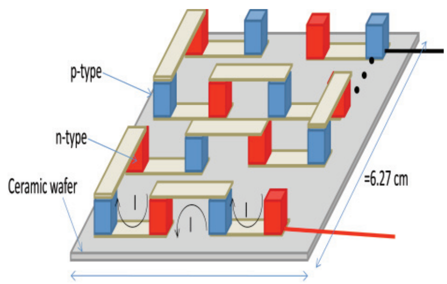


Fig. 2. Thermoelement arrangement in a TEG

In 1834, J. Peltier observed the reverse Seebeck effect known as Peltier effect. According to Peltier effect the passage of an electric current through a thermocouple produces a small heating or cooling effect depending on its direction. The interdependency between Seebeck effect and Peltier effect was later determined by W. Thomson known as Thomson effect consists of reversible heating or cooling when there is presence of both a flow of electric current and a temperature gradient.

3. Previous researches on TEG integrated cookstoves

The concept of TEG integrated stove research was first done by J .C Bass and Killander in 1996 [3]. The stove performances according to the power output and the type of cooling are summarized in the table 1.

Table 1. The name of the authors, year, type of heat sink, type of module, number of module and power output from the module

Authors (Year)	Heat sink (Cold side)	Type of module (No.)	Power (W)
Nuwayhid 2003 [4]	Natural air cooling	Peltier	1
Nuwayhid 2005 [14]	Natural air cooling	See beck	4.2
Lertsatitthanakorn 2007 [12]	Natural air cooling	See beck	2.4
Mastbergen 2007 [5]	Forced air cooling (1W)	See beck	4
Cedar 2009 [8]	Forced air cooling (1W)	See beck	2
Champier "TEGBioS" 2009 [6]	Water cooling	See beck	5
Champier "TEGBioSII" 2009 [7]	Water cooling	See beck	7.5 – 9.5 regulated
Rinalde 2010 [13]	Forced air cooling	See beck	10
S.M. O'Shaughnessy [9]	Forced air cooling	See beck	5

4. The design, materials and methods

The application of thermoelectric modules is mostly in the field of applying peltier effect. These modules are often used for refrigeration of pharmaceutical products by applying power supply. These TE modules when maintained a temperature difference on the two faces produces electricity. The peltier TE modules TEC12710 are easily available and in a cheaper rate of about 10-15 $/module. The main drawback of these modules is that when it is used as Seebeck module, then it produces power of nearly 1W. It was also observed that connecting multiple TEC12710 modules the power generation reduces. To check the performance of TEG a hot plate was taken to provide heat to the TEG. The temperature of the heat plate is raised to 500 ºC to mimic the temperature of the flame and then the TEG setup is placed upon it. To avoid the radiation loss from the hot plate that affects the cold side of the TEG, sufficient amount of glass wool was wrapped around the hot plate. The TEG is sandwiched between an aluminium plate of (10 x 8.4 x 1.2) cm^3 and the cold side was attached to heat sink. The temperatures on the hot side and the cold side were recorded continuously with K-type thermocouples.

For this application, TEG is to be selected with wider temperature range so that the module does not degrade even in higher temperature and provides sufficient power with lower heat flux. Hence two modules were considered HZ-14 and HZ-9. The thermal tolerance and electrical capacities are given below in the table 2.

Table 2. The thermal and electrical properties of HZ-14 and HZ-9

	HZ-14	HZ-9
Thermal properties		
Hot side temperature (ºC)	250	250
Cold side temperature (ºC)	30	30
Maximum heat tolerance (ºC)	400	400
Electrical properties		
Power (at matched load)	14	9
Load voltage (volts)	1.65	3.28
Internal resistance (Ω)	0.15	1.15

Current (Amps)	8	2.9
Open circuit voltage (V)	3.5	6.5

In this research, four kinds of heat sinks were tried to increase the effective surface area of the cold side and to maintain the projected cold side temperature. With each four heat sinks, the experiments were performed in actual ambient conditions. The second experiment was done by forced air cooling using a fan mounted in top of the sink. The third experiment was done by ducting the whole TEG setup with fan mounted on the top of the sink. The images of the types of heat sinks are given below in fig. 3. The performance of the four heat sinks is evaluated by measuring the open circuit voltage output from the TEG and shown in fig. 4.

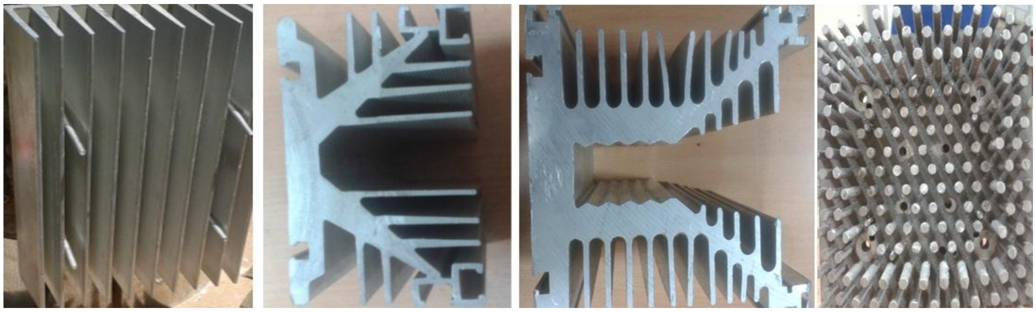


Fig. 3. (a) Vertical fins heat sink; (b) Flower fins heat sink; (c) Flower extended fins heat sink; (d) Pin type fins heat sink

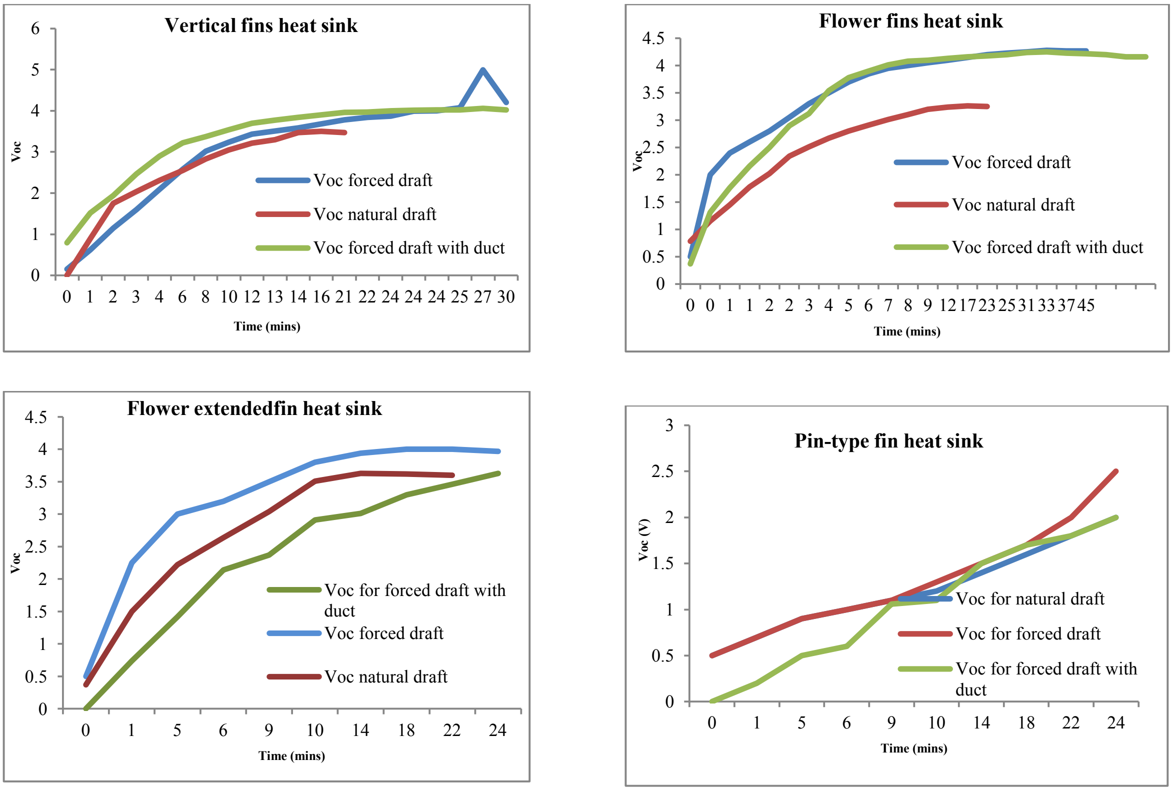
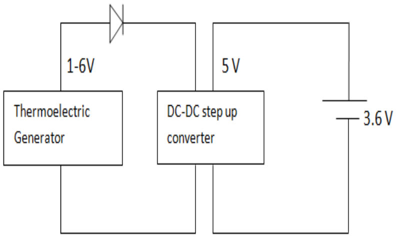


Fig. 4. Performance of TEG with (a) Vertical fins heat sink; (b) Flower fins heat sink; (c) Flower extended fins heat sink; (d) Pin type fins heat sink used with (i) ambient condition, (ii) fan mounted on sink, and (iii) fan mounted on sink with one end open duct.

The performance of the heat sink was observed till the Voc kept rising. It was observed that the flower heat sink with fan can pump out maximum heat and retain the open circuit voltage for longer period of time as compared to the other heat sinks. Hence, flower heat sink was choosen for the prototype development. For the hot side design materials like copper, aluminium and stainless steel (220) plates were tried. Though copper gave the best results during combustion period but copper could not retain much residual heat for prolonged battery charging. Copper is also very costly, so stainless steel was choosen for application. The dimensions of heat plate are (10 x 8.4 x 1.2) cm^3 and five 1 cm dia and 6.5 cm long cylindrical rods were drilled inside the heat plate. The length of rod protruding outside the plate is 6 cm and 0.5 cm length is welded inside the plate as shown in fig. 5.



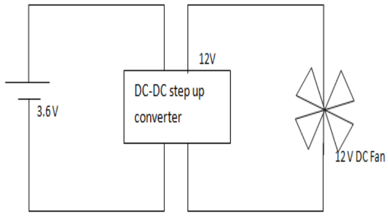


Fig 5: (a) Hot side stainless steel plate; (b) battery charging circuit by TEG; (c) fan driving circuit (battery discharging end)

The rods transfers the heat uniformly by conduction. The placement of the rods are such that the heat flux gets uniformly distributed on the TEG. The heat plate also remains exposed on the fire so that there is heating due to conduction and radiation from flame.

5. Electrical Characteristics

The TEG is prepared by applying thermal grease of boron nitrate on two sides and affixing ceramic wafers of Al_2O_3. It was observed that the power output of the HZ-14 module is very high, but the individual voltage and current output was not sufficient as per requirements. The voltage output of the HZ-14 is quite low and the current is very high. The open circuit voltage is 3.25V with ΔT of 200ºC and which is difficult to maintain by forced convection. Since, at lower temperature difference, the output voltage is very low, so a very low input DC-DC boost converter will be required for HZ-14. The authors confirmed due to the low voltage output of HZ-14, HZ-9 will be used since it gives adequate power and the V_{oc} which is accountable at lower heat flux. The two modules were experimented in external environment with the flower fins heat sink with duct and mounted by a 12 V fan on the top of the heat sink to evaluate the performance. A graph of V_{oc} versus time is shown in Fig. 6 (a).

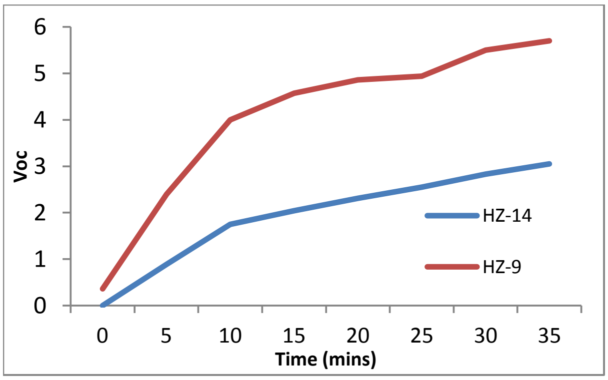


Fig. 6. (a) Voc versus time graph of HZ-14 and HZ-9; (b) Testing of TEG in hot plate with fan above duct

In the electronic part, a PFM Control step up DC-DC control converter is used to get a stable ouput voltage. The voltage output from the converter is 5 V even when the input voltage is as low as 800mV. The current output varies from 200mA-600mA. This converter is connected to the output of the TEG so that a constant voltage output can be used to charge a Li-ion battery of 3.6V, light a LED array or charge a battery. On the other hand, a 12 V DC 1.4W Sunon fan with 37 cfm is used for cooling the heat sink and to direct the the blow of air inside the combustion chamber. As a power supply to the fan, an another Li-ion battery of 3.6V is connected to 12 VSEPIC converter. It is a non-inverting dc–dc converter and can generate voltages either above or below the input range. The input current is non-pulsating, but the output currentis pulsating. The converter step up minimum voltage of 3V. Now, the DC-DC coverter when connected to load also cosumes current from the power supply apart from load current. The current consumption of the 12V step up converter should be very low so that the Li-ion battery donot get quickly discharged. It was observered that the current consumption of the converter along with load is 150mA and which is low than the charging current of the 5V converter which is 200mA-600mA. It is implicated that the battery charges at faster rate than discharge rate. This is for the first time at best of our knowledge that a domestic cookstove is able to charge a battery. The battery helps to run the fan for first few minutes of the combustion when the heat plate is not hot enough to generate electricity. Again, when cooking is finished the fan is put off so that the combusted residual fuel helps in charging the battery for a longer period.

Fig. 7. (a) Schematic of the cookstove; (b) Testing the cookstove in laboratory condition; (c) Mobile charging by TEG cookstove.

6. Conclusion

Prototypes of TEG integrated stoves have been tested in Biomass Cookstove Testing Laboratory in Indian Institute of Technology, New Delhi and successfully developed. The performance of the TEG integrated cookstove is evaluated first byWater boiling test (WBT) following the Bureau of Indian Standards. The TEG integrated cookstove is able to boil 6.1 kg of water in 30 minutes. The power generated from the TEG 3 to 5 Watt. The generated power is basically used for battery charging and lighting. The field trials of 100 TEG integrated cookstoves is running and under observation for the final feedbacks of the user, determining fuel consumption and testing of emissions.

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Biography

Risha Mal is a full-time research scholar in Indian Institute of Technology, New Delhi, India. Her research interest includes renewable and sustainable energy technology and rural developments. She received her Master of Technology in Electronics & Communication Engineering [VLSI Design] from National Institute of Technology, Kurukshetra, India. She received her Bachelor of Technology in Electrical and Electronics Engineering from GGSIP University, New Delhi. She has published 4 international journal papers in various fields and attended many International conferences.